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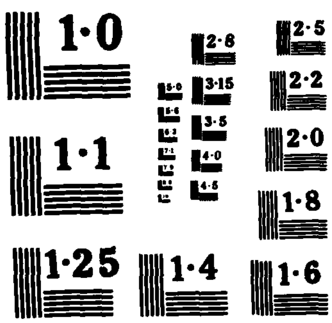

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Report SAIC-84/1805

A MODEL OF ACOUSTIC BACKSCATTER FROM ARCTIC SEA ICE

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Technical Report

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A model of acoustic backscatter from Arctic Sea ridge keels is developed. The model is demonstrated to produce good agreement with data. It is a composite surface scattering theory based on diffractive scattering from small scale roughness on the flanks of randomly oriented triangular ridge keels.

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A MODEL OF ACOUSTIC BACKSCATTER FROM ARCTIC SEA ICE

1. INTRODUCTION

1.1 Backscatter levels. Acoustic backscatter levels from Arctic sea-ice have been observed[1-4] to be much stronger than observed levels in the open ocean. Mellen[5] demonstrated that observed levels were inconsistent with the predictions of the perturbation-type spectral scattering theories from a rough pressure release surface, published by Marsh[6] and later by Bass and Fuks[7]. The major failing of the perturbation models is to neglect the effect of large-scale surface features.

1.2 Composite surface method. Kuryanov[8] and Brown[9] have devised the composite surface method to combine the effects of large-scale surface features and small-scale roughness. In Brown's version of the composite surface theory, the surface roughness spectrum is divided, at a particular wavenumber, into low- and high-wavenumber portions. The low-wavenumber portion is used to calculate the variance of a Gaussian distribution for the slope of the surface. The high-wavenumber portion is used in a perturbation-type model to calculate diffractive scattering strength for given in-coming and out-going directions. These in-coming and out-going directions are defined relative to the scattering surface, and hence the local scattering strength depends on the local slope of the scattering surface. The mean backscattering strength predicted by the composite surface technique is the expected value of the local scattering strength with respect to the Gaussian distribution of slope.

1.3 Triangular ridge model. Unfortunately, the slope distribution of Arctic ice is not Gaussian in nature. The composite surface theory with a Gaussian distribution of slope, while giving some improvement, still fails to predict observed backscatter levels. In the next section, a composite surface theory based on scattering from rough triangular ridges will be derived. The triangular ridge model gives good agreement with backscatter data from Arctic sea ice.

2. THE SLOPE MODEL

2.1 Ridge keel structure. The underside surface of Arctic sea-ice consists of relatively smooth stretches of ice interrupted by large linear ridge-keel structures. These keels are piles of ice rubble, with steep flanks. In the triangular-ridge composite model proposed here, the ice-ridge keels are modeled as randomly oriented prisms of triangular cross section, whose flanks have some fixed slope angle. Superimposed on the triangular structure is small-scale roughness, characterized by the large-wavenumber portion of the surface roughness spectrum. This small-scale roughness is due to the small pieces of rubble of which the keel is composed.

2.2 Intervening ice roughness. Between the keels, it is assumed the intervening ice is perfectly flat. One consequence of this is that backscattering only occurs at the ridge keels. This is consistent with observations by Berkson, et al.[10], using a narrow-band scanning sonar. Their results indicate: "(1) very high level backscattering from well-defined under-ice ridges and (2) very low levels of backscattering between ridges." The roughness of ice lying between the ridges is not negligible, but it produces a negligible contribution to acoustic backscatter at small grazing angles. The authors speculate that the coherence of the forward propagating energy may depend on the roughness of the intervening, "undeformed" ice, since high frequency energy striking the sloping side of a ridge will generally be scattered out of the propagation channel at high angles.

2.3 Roughness spectrum. All calculations of scattering strength in this article are based on the one-dimensional folded roughness spectrum published by Mellen[5]. A good fit to this spectrum is given by the function[11]:

$$G_1\,(k_x) = \frac{B}{\left(k_o^2 + k_x^2\right)^{3/2}},$$

where

$$B = .013,$$

$$k_o = .05 \text{ (inverse meters)}.$$

The isotropic two-dimensional spectrum, F_2, associated with G_1 is obtained using the Hankel transform. This integral can be carried out in closed form to obtain:

$$F_2\,(|k|) = \frac{B}{\pi\left(k_o^2 + |k|^2\right)^2},$$

where k is the two-dimensional wave vector:

$$k = \left(k_x,\ k_y\right).$$

2.4 Spectrum correction factor. The roughness spectrum is used to characterize the roughness on the ridge keels. Mellen's spectrum for the entire surface can be thought of as a weighted average of the roughness spectra for the ridged and smooth portions of the surface. A correction factor must be applied to Mellen's spectrum to account for the fact that all roughness is localized in the keels. This factor is

$$1/P_R,$$

where P_R is the fraction of the surface area that is ridged.

2.5 Ridge orientation. The orientation of the ridges is assumed to be random in this model. However, sound propagating in a given direction will tend to collide most often with those ridges lying perpendicular to its path. The distribution of ridge orientation with respect to a ray path is a variation on the Buffon needle problem, discussed in Feller.[12] Let ϕ be the angle between the ridge axis and the perpendicular to the track of the ray along the ice. The probability density for the angle ϕ, given that the ray collided with the ridge, is:

$$\frac{1}{2} \cos \phi \, d\phi, \text{ where } \frac{-\pi}{2} < \phi < \frac{\pi}{2} .$$

2.6 Shadowing by ridge keels. Shadowing by ridge keels works to increase scattering strength at low grazing angles, since it is the flat portion of the ice surface which will be shadowed. The probability of scattering from a ridge on a given bounce is thus enhanced at low grazing angles. The probability that a ray will be scattered from the front of a ridge is estimated to be:

$$P_S = (h/\tan\gamma + (\pi/2)\, w_o)/S,$$
with maximum value 1,

where h is the average keel depth,

w_o is half the average keel width,

S is the average keel spacing, and

γ is the grazing angle of the incident ray.

The formula for P_S is the ratio of the length of the ridge shadow to the mean spacing between ridges. The length of the shadow is the mean distance from the front of the ridge to the top of the ridge along the track, including the effects of orientation, $(\pi/2)\, w_o$, plus the distance from the peak of the ridge back to the shadow image of the peak, $h/\tan\gamma$.

2.7 Mean backscattering strength. The mean backscattering strength of a small patch of the surface is the local backscattering strength from a ridge at a given orientation, averaged over the ridge orientation, and multiplied by the probability that the patch is on a ridge. Following Bass and Fuks[7], the local backscattering strength of a patch on a ridge at a given orientation ϕ is:

$$S(\phi) = 4\, k^4\, (\alpha \cdot n)^4\, \frac{1}{P_R}\, F_2\, \left(2k\, \left(1-(\alpha \cdot n)^2\right)^{1/2}\right),$$

where:
- α is the unit incoming wave vector $(\cos\gamma, 0, \sin\gamma)$,
- γ is the grazing angle of the ray,
- n is the unit normal to the ridge surface $(\cos\phi \cdot \sin\theta, \sin\phi \cdot \sin\theta, \cos\theta)$,
- θ is the base angle of the triangular ridge cross section,
- k is the acoustic wavenumber,
- P_R is the percentage of the surface covered by ridges, and
- F_2 is the two-dimensional isotropic roughness spectrum.

The mean backscattering strength is:

$$\overline{S} = P_S \int_{-\pi/2}^{\pi/2} S(\phi)\, \frac{\cos\phi}{2}\, d\phi.$$

3. DISCUSSION OF RESULTS

3.1 Backscatter data. Estimates of acoustic backscatter based on composite surface theories are compared with measured data from three locations[4] in Figures 1 and 2. The data were taken in the frequency band from 1.28-2.56 kHz. Above 320 Hz there is very little frequency dependence.

3.2 Gaussian slope model-data comparison. In Figure 1, the data are compared with the prediction at 1.81 kHz of a composite surface model with Gaussian slope distribution. The prediction lies well below the measured values. Furthermore, the model exhibits substantial frequency dependence in our implementation.

3.3 Triangular ridge model-data comparisons. In Figure 2 the data is compared with two predictions at 1.81 kHz, based on a triangular ridge model. The predictions, using triangular ridge shapes with base angles of 30° and 35°, respectively, give good agreement with observed backscatter levels. Furthermore, the prediction is independent of frequency for higher frequencies, in quantitative agreement with data in Brown and Milne[4] for five octave bands from 452 Hz to 7.24 kHz. The characteristics of the triangular ridges are:

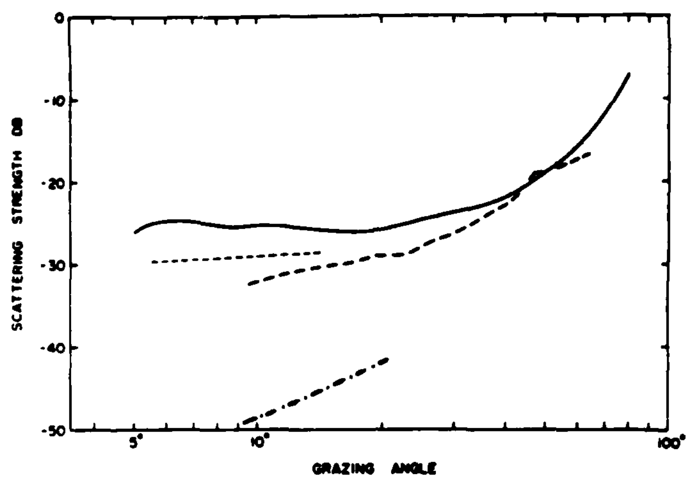

Figure 1

Estimated backscattering strength (-•-•-) at 1.81-kHz using a composite surface model with Gaussian slope distribution is compared with data from Brown and Milne[4] for Spring and Summer pack ice at three locations in the frequency band 1.28 to 2.56 kHz .

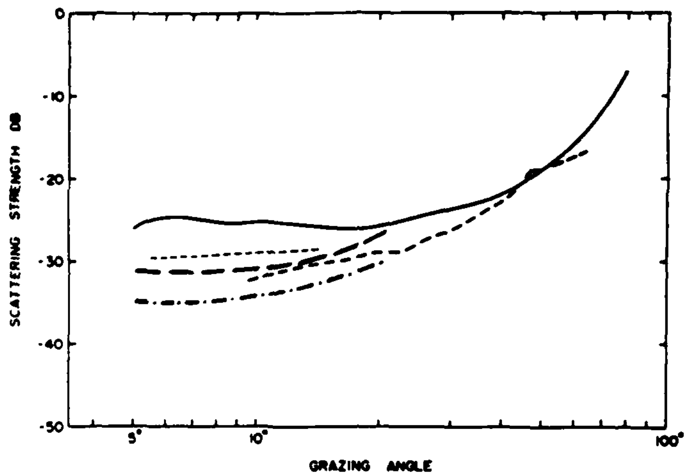

Figure 2

Estimated backscattering strength at 1.81-kHz using a composite surface model with triangular ridge shapes having a base angle of 30° (-•-•-) and 35° (----) are compared with data from Brown and Milne[4] for Spring and Summer pack ice at three locations in the frequency band 1.28 to 2.56 kHz .

3.3.1 Mean height (h) = 4.3 m

3.3.2 Mean spacing (S) = 100 m

3.3.3 Base angle slope = 30° or 35°.

4. CONCLUSIONS

4.1 Diffraction scattering on steep slopes. The composite surface scattering theory based on triangular ridge keels gives reasonable agreement with data. The technique is based on discrete ridge statistics and roughness spectra which can be measured from a submarine platform. A base angle, sometimes called the angle of repose, of the triangular ridges of about 35° seems to give good results. It is the fact that scattering takes place primarily from steeply sloped surfaces, in the triangular ridge model, which contributes most to the improved agreement over the Gaussian model. The actual scattering mechanism is diffractive scattering from small-scale roughness, as estimated from the roughness spectrum.

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